

Claims

What is claimed is:

- 5 1. A waveguide grating coupler for coupling light between a waveguide and an optical element having a substantially Gaussian mode profile, said waveguide grating coupler comprising:

a planar guiding portion optically connected to said waveguide, said planar guiding portion having first and second ends and an optical power distribution therein
10 that decreases between said first and second ends; and

a plurality of elongate scattering elements having respective scatter cross-sections arranged along at least a portion of said planar guiding portion to couple light having a substantially Gaussian intensity distribution between said planar guiding portion and said optical element, said elongate scattering elements having at least one characteristic which
15 varies in magnitude among at least a group of said elongate scattering elements, said magnitude of said characteristic controlling at least in part said scatter cross-sections of said elongate scattering elements,

wherein said magnitude of said characteristic of said group of elongate scattering elements varies irregularly, said magnitude for said group of elongate scattering elements
20 changing with position along said planar guiding portion at a rate that is discontinuous.

2. The waveguide grating coupler of Claim 1, wherein said optical element comprises an optical fiber.

- 25 3. The waveguide grating coupler of Claim 1, wherein said magnitude of said characteristic changes with position along said planar grating portion so as to provide an optical output substantially matching said Gaussian mode profile of said optical element.

4. The waveguide grating coupler of Claim 1, wherein said rate of change in
30 magnitude of said characteristic for said group of elongate scattering elements increases and decreases between said first and second ends.

5. The waveguide grating coupler of Claim 1, wherein said magnitude of said characteristic for said group of elongate scattering elements both increases and decreases between said first and second ends.

6. The waveguide grating coupler of Claim 1, wherein said planar guiding portion has sidewalls to confine light in a transverse direction.

7. The waveguide grating coupler of Claim 1, wherein said planar guiding portion is selected from the group consisting of a channel waveguide, a ridge waveguide, a strip loaded waveguide, and a strip loaded waveguide having a low index transition region.

8. The waveguide grating coupler of Claim 1, wherein said optical power distribution decreases between said first and second ends of said planar guiding portion substantially in accordance with a relationship defined the complementary error function.

9. The waveguide grating coupler of Claim 1, wherein said at least one characteristic is selected from the group consisting of grating width, grating height, grating spacing, grating depth, and index of refraction of said elongate scattering elements.

10. The waveguide grating coupler of Claim 1, wherein a plot of the magnitudes of said characteristic associated with said group of elongate scattering elements versus position along said guiding portion includes more than two elongate scattering elements substantially offset from a single exponential or Gaussian function that is fit to said plot.

11. The waveguide grating coupler of Claim 1, wherein said plurality of elongate scattering elements comprises at least 20 elongate scattering elements.

12. The waveguide grating coupler of Claim 1, wherein said magnitude of said characteristic at different positions along said planar grating is selected such that the variation $F(z)$ in scatter cross-sections of the group of elongate scattering elements as a function of longitudinal distance across the group of elongate scattering elements satisfies

the following relationship:

$$G(z) = F(z) E(z)$$

where $G(z)$ corresponds to said substantially Gaussian mode profile of said optical element, and $E(z)$ corresponds to optical power distribution that decreases between said
5 first and second ends.

13. The waveguide grating coupler of Claim 1, wherein said waveguide grating coupler couples a substantially planar wave between said waveguide and said optical element, said substantially planar wave oriented at an angle with respect to said planar -
10 guiding portion, said elongate scattering elements in said planar guiding portion having spacing selected to scatter light within said waveguide out of said planar guiding portion into a beam directed at said angle.

14. The waveguide grating coupler of Claim 1, wherein said elongate scattering
15 elements in said planar guiding portion have non-uniform spacing selected to scatter light within said waveguide out of said planar guiding portion into a beam having a desired beam shape.

15. The waveguide grating coupler of Claim 1, further comprising a substrate, said
20 planar guiding portion being disposed over said substrate.

16. The waveguide grating coupler of Claim 15, wherein said substrate comprises a silicon wafer.

25 17. The waveguide grating coupler of Claim 16, wherein said substrate further comprises a silicon dioxide layer formed on said silicon wafer.

18. The waveguide grating coupler of Claim 17, wherein said substrate further
30 comprises one or more layers of material formed on said silicon wafer.

19. A waveguide grating coupler for coupling light between a waveguide and an optical element having a substantially Gaussian mode profile, said waveguide grating coupler comprising:

5 a planar guiding portion optically connected to said waveguide, said planar guiding portion having first and second ends and an optical power distribution therein that decays between said first and second ends; and

a plurality of elongate scattering elements having respective scatter cross-sections arranged along at least a portion of said planar guiding portion to couple light having a substantially Gaussian intensity distribution between said planar guiding portion and said optical element, said elongate scattering elements having at least one characteristic which varies in magnitude, said magnitude of said characteristic controlling at least in part said scatter cross-sections of said elongate scattering elements,

15 wherein said magnitude of said characteristic for said plurality of elongate scattering elements varies non-linearly with position along said planar guiding portion, and a plot of the magnitudes of said characteristic associated with said plurality of elongate scattering elements versus position along said guiding portion includes at least one elongate scattering element substantially offset from a single exponential or Gaussian that is fit to said plot.

20 20. The waveguide grating coupler of Claim 19, wherein said optical element comprises an optical fiber.

21. The waveguide grating coupler of Claim 19, wherein said magnitude of said characteristic changes with position along said planar grating portion so as to provide an optical output substantially matching said Gaussian mode profile of said optical element.

22. The waveguide grating coupler of Claim 19, wherein a plot of the magnitudes of said characteristic associated with said plurality of elongate scattering elements versus position along said guiding portion includes more than two elongate scattering elements substantially offset from a single exponential or Gaussian function that is fit to said plot.

23. The waveguide grating coupler of Claim 19, wherein said magnitude of said characteristic both increases and decreases between said first and second ends.

5 24. The waveguide grating coupler of Claim 19, wherein said plurality of elongate scattering elements comprises at least 20 elongate scattering elements.

25. The waveguide grating coupler of Claim 19, wherein said planar guiding portion has sidewalls to confine light in a transverse direction.

10 26. The waveguide grating coupler of Claim 25, wherein said planar guiding portion is selected from the group consisting of a channel waveguide, a ridge waveguide, a strip loaded waveguide, and a strip loaded waveguide having a low index transition region.

15 27. The waveguide grating coupler of Claim 19, wherein said at least one characteristic is selected from the group consisting of grating width, grating height, grating depth, grating spacing, and index of refraction of said elongate scattering elements.

20 28. The waveguide grating coupler of Claim 19, wherein said characteristic comprises grating width and said plurality of elongate scattering elements have width selected such that the variation $F(z)$ in scatter cross-sections of the plurality of elongate scattering elements as a function of longitudinal distance across the plurality of elongate scattering elements satisfies the following relationship:

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$$G(z) = F(z) E(z)$$

where $G(z)$ corresponds to said substantially Gaussian mode profile of said optical element, and $E(z)$ corresponds to optical power distribution that decreases between said first and second ends.

30 29. The waveguide grating coupler of Claim 19, wherein said waveguide grating coupler couples a substantially planar wave between said waveguide and said optical

element, said substantially planar wave oriented at an angle with respect to said planar -
guiding portion, said elongate scattering elements in said planar guiding portion having
spacing selected to scatter light within said waveguide out of said planar guiding portion
into a beam directed at said angle.

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30. The waveguide grating coupler of Claim 19, wherein said elongate scattering
elements in said planar guiding portion having non-uniform spacing selected to scatter
light within said waveguide out of said planar guiding portion into a beam having a
desired beam shape.

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31. A waveguide grating coupler for coupling light between a waveguide and an
optical element having a substantially Gaussian mode profile, said waveguide grating
coupler comprising:

a planar guiding portion optically connected to said waveguide, said planar guiding
15 portion having first and second ends and an optical power distribution therein that decay
between said first and second ends; and

a plurality of elongate scattering elements having respective scatter cross-sections
arranged to couple light having a substantially Gaussian intensity distribution between
said planar guiding portion and said optical element, said elongate scattering elements
20 having at least one characteristic which varies in magnitude among at least some of said
elongate scattering elements, said magnitude of said characteristic controlling at least in
part said scatter cross-sections of said elongate scattering elements, said scatter cross-
section depending on the magnitude of the characteristic as defined by a non-
monotonically varying relationship between said scatter cross-section and said magnitude,

25 wherein said elongate scattering elements are relatively positioned to provide said
substantially Gaussian intensity distribution of said coupled light and said decay of said
optical power distribution in said coupler.

32. The waveguide grating coupler of Claim 31, wherein said non-monotonically varying relationship between said scatter cross-section and said magnitude is oscillatory such that it has a plurality of local extrema.

5 33. The waveguide grating coupler of Claim 31, wherein said non-monotonically varying relationship between said scatter cross-section and said magnitude has portion with negative slope and portions with positive slope.

34. The waveguide grating coupler of Claim 31, wherein said optical element
10 comprises an optical fiber.

35. The waveguide grating coupler of Claim 31, wherein said magnitude of said characteristic for said group of elongate scattering elements both increases and decreases between said first and second ends.

15 36. The waveguide grating coupler of Claim 31, wherein said planar guiding portion has sidewalls to confine light in a transverse direction.

37. The waveguide grating coupler of Claim 31, wherein said planar guiding portion
20 is selected from the group consisting of a channel waveguide, a ridge waveguide, a strip loaded waveguide, and a strip loaded waveguide having a low index transition region.

38. The waveguide grating coupler of Claim 31, wherein said optical power distribution decreases between said first and second ends of said planar guiding portion
25 substantially in accordance with the complementary error function.

39. The waveguide grating coupler of Claim 31, wherein said at least one characteristic is selected from the group consisting of grating width, grating height, grating spacing, grating depth, and index of refraction of said elongate scattering
30 elements.

40. The waveguide grating coupler of Claim 31, wherein a plot of the magnitudes of said characteristic associated with said group of elongate scattering elements versus position along said guiding portion includes more than two elongate scattering elements substantially offset from a single exponential or Gaussian function that is fit to said plot.

41. The waveguide grating coupler of Claim 31, wherein said plurality of elongate scattering elements comprises at least 20 elongate scattering elements.

42. The waveguide grating coupler of Claim 31, wherein said characteristic comprises grating width and said group of elongate scattering elements have width selected such that the variation $F(z)$ in scatter cross-sections of the group of elongate scattering elements as a function of longitudinal distance across the group of elongate scattering elements satisfies the following relationship:

$$G(z) = F(z) E(z)$$

where $G(z)$ corresponds to said substantially Gaussian mode profile of said optical element, and $E(z)$ corresponds to optical power distribution that decreases between said first and second ends.

43. The waveguide grating coupler of Claim 31, wherein said waveguide grating coupler couples a substantially planar wave between said waveguide and said optical element, said substantially planar wave oriented at an angle with respect to said planar - guiding portion, said elongate scattering elements in said planar guiding portion having spacing selected to scatter light within said waveguide out of said planar guiding portion into a beam directed at said angle.

44. The waveguide grating coupler of Claim 31, wherein said elongate scattering elements in said planar guiding portion having non-uniform spacing selected to scatter light within said waveguide out of said planar guiding portion into a beam having a desired beam shape.

45. A waveguide grating coupler for coupling light between a waveguide and an optical element having a substantially Gaussian mode profile, said waveguide grating coupler comprising:

a planar guiding portion optically connected to said waveguide, said planar guiding portion having first and second ends and an optical power distribution therein that decreases between said first and second ends; and

a plurality of elongate scattering elements having respective scatter cross-sections arranged to couple light having a substantially Gaussian intensity distribution between said planar guiding portion and said optical element, said elongate scattering elements having widths which vary in magnitude among at least some of said elongate scattering elements, said widths controlling at least in part said scatter cross-sections of said elongate scattering elements as defined by a relationship between widths and scatter cross-sections, said relationship including at least two widths that provide substantially similar scatter cross-sections,

wherein said elongate scattering elements are relatively positioned to provide said substantially Gaussian intensity distribution of said coupled light and said decrease of said optical power distribution in said coupler.

46. The waveguide grating coupler of Claim 45, wherein said optical element comprises an optical fiber.

47. The waveguide grating coupler of Claim 45, wherein said magnitude of said grating widths changes with position along said planar grating portion so as to provide an optical output substantially matching said Gaussian mode profile of said optical element.

48. The waveguide grating coupler of Claim 45, wherein said magnitude of said grating widths both increases and decreases between said first and second ends.

49. The waveguide grating coupler of Claim 45, wherein said planar guiding portion has sidewalls to confine light in a transverse direction.

50. The waveguide grating coupler of Claim 45, wherein said planar guiding portion is selected from the group consisting of a channel waveguide, a ridge waveguide, a strip loaded waveguide, and a strip loaded waveguide having a low index transition region.

5 51. The waveguide grating coupler of Claim 45, wherein said optical power distribution decreases between said first and second ends of said planar guiding portion substantially in accordance with a relationship defined by the complementary error function.

10 52. The waveguide grating coupler of Claim 45, wherein a plot of the magnitudes of said grating widths versus position along said guiding portion includes more than two elongate scattering elements substantially offset from a single exponential or Gaussian function that is fit to said plot.

15 53. The waveguide grating coupler of Claim 45, wherein said plurality of elongate scattering elements comprises at least 20 elongate scattering elements.

20 54. The waveguide grating coupler of Claim 45, wherein said plurality of elongate scattering elements have width selected such that the variation $F(z)$ in scatter cross-sections of the plurality of elongate scattering elements as a function of longitudinal distance across the plurality of elongate scattering elements satisfies the following relationship:

$$G(z) = F(z) E(z)$$

25 where $G(z)$ corresponds to said substantially Gaussian mode profile of said optical element, and $E(z)$ corresponds to optical power distribution that decreases between said first and second ends.

30 55. The waveguide grating coupler of Claim 45, wherein said waveguide grating coupler couples a substantially planar wave between said waveguide and said optical element, said substantially planar wave oriented at an angle with respect to said planar -

guiding portion, said elongate scattering elements in said planar guiding portion having spacing selected to scatter light within said waveguide out of said planar guiding portion into a beam directed at said angle.

5 56. The waveguide grating coupler of Claim 45, wherein said elongate scattering elements in said planar guiding portion having non-uniform spacing selected to scatter light within said waveguide out of said planar guiding portion into a beam having a desired beam shape.

10 57. An integrated optical apparatus, comprising:
a planar waveguide having an elongate guiding portion and a grating coupler, said grating coupler comprising a grating comprising a plurality of elongate scattering elements including a first elongate scattering element that is segmented into scattering portions and a second elongate scattering element that is unsegmented.

15 58. The integrated optical apparatus of Claim 57, wherein said first segmented elongate scattering element comprises raised sections of material forming said scattering portions.

20 59. The integrated optical apparatus of Claim 57, wherein said first segmented elongate scattering element comprises cavities patterned in material forming said scattering portions.

60. The integrated optical apparatus of Claim 57, wherein said first segmented
25 elongate scattering element comprises alternating regions of different material.

61. The integrated optical apparatus of Claim 57, wherein said first segmented
elongate scattering element comprises alternating regions of material having different
properties.

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62. The integrated optical apparatus of Claim 57, wherein said first segmented elongate scattering element comprises scattering portions that are elongated and have rounded edges.

5 63. The integrated optical apparatus of Claim 57, wherein said first segmented elongate scattering element comprises scattering portions having shapes selected from the group consisting of rectangular, square, circular, and elliptical.

64. The integrated optical apparatus of Claim 57, wherein said first segmented
10 elongate scattering element comprises scattering portions having different scatter cross-sections.

65. The integrated optical apparatus of Claim 57, wherein said first segmented elongate scattering element comprises scattering portions having different shapes.

15 66. The integrated optical apparatus of Claim 57, wherein said first segmented elongate scattering element comprises scattering portions having different sizes.

67. The integrated optical apparatus of Claim 57, wherein said first segmented
20 elongate scattering element comprises scattering portions having different materials.

68. The integrated optical apparatus of Claim 57, wherein said first segmented elongate scattering element comprises scattering portions having different spacings therebetween.

25 69. The integrated optical apparatus of Claim 57, further comprising a third elongate scattering element, said third elongate scattering element being segmented into scattering portions, wherein said first segmented elongate scattering element comprises scattering portions having different scatter cross-sections than said third segmented elongate
30 scattering element.

70. The integrated optical apparatus of Claim 57, further comprising a third elongate scattering element, said third elongate scattering element being segmented into scattering portions, wherein said first segmented elongate scattering element comprises scattering portions having different shapes than said scattering portions in said third segmented elongate scattering element.

71. The integrated optical apparatus of Claim 57, further comprising a third elongate scattering element, said third elongate scattering element being segmented into scattering portions, wherein said first segmented elongate scattering element comprises scattering portions having different sizes than said scattering portions in said third segmented elongate scattering element.

72. The integrated optical apparatus of Claim 57, further comprising a third elongate scattering element, said third elongate scattering element being segmented into scattering portions, wherein said first segmented elongate scattering element comprises scattering portions comprising different materials than said scattering portions in said third segmented elongate scattering element.

73. The integrated optical apparatus of Claim 57, further comprising a third elongate scattering element, said third elongate scattering element being segmented into scattering portions, wherein said first segmented elongate scattering element comprises scattering portions having different grating spacings than said scattering portions in said third segmented elongate scattering element.

74. The integrated optical apparatus of Claim 57, wherein said elongate scattering elements are curved.

75. The integrated optical apparatus of Claim 57, wherein said coupler comprises at least 20 elongate scattering elements.

76. The integrated optical apparatus of Claim 57, wherein at least 5 of said elongate scattering elements are segmented.

77. An integrated optical apparatus, comprising:

5 a planar waveguide having an elongate guiding portion and a grating coupler, said coupler having first and second ends, said first end adjacent said elongate guiding portion, said coupler comprising a plurality of elongate scattering elements having respective scatter cross-sections, at least one of said elongate scattering element being segmented into portions so as to reduce the scatter cross-section of said at least one elongate scattering element, said at least one segmented elongate scattering element disposed adjacent said first coupler end, said coupler further comprising a first unsegmented elongate scattering element adjacent said at least one segmented elongate scattering element, said first unsegmented elongate scattering element having a greater scatter cross-section than the segmented elongate scattering element.

15 78. The integrated optical apparatus of Claim 77, wherein said coupler includes a second unsegmented elongate scattering element disposed towards said second coupler end relative to said first unsegmented elongate scattering element, said second unsegmented elongate scattering element having a scatter cross-section greater than that of said first unsegmented elongate scattering element.

79. The integrated optical apparatus of Claim 77, wherein said coupler comprises at least 20 elongate scattering elements.

25 80. The integrated optical apparatus of Claim 77, wherein at least 5 of said elongate scattering elements are segmented.

81. The integrated optical apparatus of Claim 77, wherein said plurality of elongate scattering elements are curved.

82. The integrated optical apparatus of Claim 77, wherein said plurality of elongate scattering elements have a curvature that follows an elliptical path defined by two foci.

83. The integrated optical apparatus of Claim 77, wherein said segmented elongate scattering element comprises raised sections of material.

84. The integrated optical apparatus of Claim 77 wherein said segmented elongate scattering element comprises cavities patterned in material.

85. The integrated optical apparatus of Claim 77, wherein said segmented elongate scattering element comprises alternating regions of different material.

86. The integrated optical apparatus of Claim 77, wherein said segmented elongate scattering element comprises alternating regions of material having different properties.

87. An integrated optical apparatus, comprising:

a planar waveguide having an elongate guiding portion and a grating coupler, said coupler having first and second ends, said first end adjacent said elongate guiding portion, said coupler comprising a plurality of elongate scattering elements having respective scatter cross-sections, at least a first and a second of said elongate scattering elements being segmented into portions so as to reduce the scatter cross-section of said first and second elongate scattering elements, said first segmented elongate scattering element disposed towards said first coupler end relative to said second segmented elongate scattering element, said first segmented elongate scattering element having a scatter cross-section less than that of said second segmented elongate scattering element.

88. The integrated optical apparatus of Claim 87, wherein said plurality of elongate scattering elements further comprises an unsegmented elongate scattering element.

89. The integrated optical apparatus of Claim 88, wherein said unsegmented elongate scattering element is disposed towards said second coupler end relative to said first and second segmented elongate scattering elements, and said segmented elongate scattering

element has a scatter cross-section greater than that of said first and second segmented elongate scattering elements.

90. The integrated optical apparatus of Claim 87, wherein said first and second segmented elongate scattering elements are aligned along a curved path.

91. The integrated optical apparatus of Claim 87, wherein said first and second segmented elongate scattering elements are aligned along elliptical paths.

92. The integrated optical apparatus of Claim 87, wherein said segmented elongate scattering elements comprise raised sections of material.

93. The integrated optical apparatus of Claim 87, wherein said segmented elongate scattering elements comprise strips of material.

94. The integrated optical apparatus of Claim 87, wherein said first and second segmented elongate scattering element comprise a plurality of separated segments and said separation between said segments is larger in said first segmented elongate scattering element than said second segmented elongate scattering element to provide increasing scatter cross-sections.

95. The integrated optical apparatus of Claim 87, wherein said first and second segmented elongate scattering elements comprise a plurality of separated segments and said segments are larger in said second segmented elongate scattering element than said first segmented elongate scattering element to provide increasing scatter cross-sections.

96. The integrated optical apparatus of Claim 87, wherein said waveguide comprises a planar waveguide having sidewalls to confine light in a transverse direction.

97. The integrated optical apparatus of Claim 96, wherein said waveguide is selected from the group consisting of a channel waveguide, a ridge waveguide, a strip loaded waveguide, and a strip loaded waveguide having a low index transition region.